LETTERS TO NATURE

PHYSICAL SCIENCES

Nature of the Secondary Component of Beta Lyrae

AMONG known binary systems suggested[1-6] as possibly harbouring a black hole as a secondary, ε Aur[7-11] and β Lyr[12,13] have drawn much current attention. Both systems consist of a luminous massive primary and a faint (or invisible) secondary, whose presence is revealed largely by the eclipses it produces. From the mass function alone, each secondary must be fairly massive and is probably in the form of a disk (or ring) containing an underluminous star. This latter star has been suggested as being a collapsar.

In the case of β Lyr at least, an alternative hypothesis regarding the nature of the secondary star seems possible. We suggest that it may be a massive "main-sequence" star in rapid, nonuniform rotation. Specifically, we are adopting Huang's[14] and Woolf's[15] basic model for β Lyr, consisting of a faint star embedded in a circulating disk that has formed as a result of the primary's overflowing its Roche lobe during evolutionary envelope expansion (except that, in our picture, the disk need not be massive). There are two other examples of stars whose underluminosity is probably due to high angular momentum. The importance of these two stars is that they are normal enough not to be accused of harbouring a black hole.

R. S. has recently prepared a catalogue containing data for seventeen main-sequence OB components of twelve massive binary systems, for which reliable masses and luminosities of both components are available; most of the luminosities are based on distance moduli of the clusters to which these selected systems belong. In a plot of mass against spectral type (or effective temperature), all but two of the components lie within the theoretical main-sequence band based on nonrotating stellar models (with a small allowance for uncertainty of the "normal" Population I chemical composition). A similar result is obtained in a plot of mass versus luminosity.

Table 1 Deficiency of the Luminosity and Effective Temperature of the Primaries of μ^1 Sco and V356 Sgr with Respect to Nonrotating Stellar Models

Primary	Sp	$M/M_\odot$	M_{bol}	$\log T_e$	$\delta\lvert M_{bol}\rvert$	$\delta \log T_e$
μ^1 Sco	B1.5 V	14	−4.5	4.33	~1.5	~0.10
V356 Sgr	B3 V	12	−3.6	4.25	~1.5	~0.10

The two exceptions, μ^1 Sco and V356 Sgr, have primaries that are very cool and underluminous for their masses, as is shown by Table 1. For V356 Sgr, the luminosity has been determined only from the effective temperature combined with the radius given by the orbit solution; but for μ^1 Sco, three independent methods have been used: first, effective temperature and radius from the orbit; second, photometric distance modulus from membership in Sco OB2; third, kinematic distance modulus based on membership in the Sco-Cen moving group. All three methods give virtually the same luminosity for μ^1 Sco. Harris, Strand and Worley[16] classify the masses and radii from the orbits of μ^1 Sco and V356 Sgr as fairly reliable, while Wood[17] designates them as "well determined".

One evolutionary feature differentiates the primaries of μ^1 Sco and V356 Sgr from all the other OB components under consideration (except Z Vul). They are almost certainly the former secondaries in systems that underwent a mass exchange, since the present subgiant secondaries have very low masses but are more highly evolved than the primaries[18]. L. B. L. has pointed out previously[15] that, during the mass-exchange process, appreciable orbital angular momentum is expected to be picked up as rotational angular momentum by the (new) primary. Turbulent convection may, on theoretical grounds, be supposed to mix the star, chemically and rotationally, on a fast (Kelvin) time scale, tending to produce a "zero-age" main sequence star in approximately uniform rotation[19]. But viscous forces near the surface where the primary is still attached to the remnant of the massive disk, and tidal forces due to the presence of the companion, will tend to slow down the rotation of the stellar envelope whereas the denser core will be much less retarded. But even if the mixing does not extend to the centre and thus leaves the core rotating with its initial (small) angular momentum, the reduced central pressure, compared with that in a nonrotating star of the same mass in which the weight of the overlying layers is fully felt (since it is not reduced by centrifugal force), will produce the same effect of a lowering of the surface luminosity as does a reduced central pressure due to fast rotation in the core. Our point is that, regardless of the extent of internal mixing induced by the process of mass accretion, the primaries of μ^1 Sco and V356 Sgr are expected to be in rapid, highly differential rotation, compared with the probably uniform rotation of the other 15 stars in our sample. The known surface rotational velocity of the primary of μ^1 Sco, $V_e = 220$ km/s, is consistent with the values for the other stars. In fact, synchronism of the surface rotational period of the primary with the revolutional period seems to have been already attained in μ^1 Sco, though not in V356 Sgr[20].

It is well known that a uniform rotation imposed on stellar models has very little effect on the surface luminosity but reduces slightly the effective temperature (making the spectral type appear later)[21]. Recent models of Bodenheimer[22] for massive main-sequence stars in highly nonuniform rotation show that both luminosity and effective temperature can be drastically reduced by concentrating angular momentum to the centre of the star, even for modest surface rotational velocities. A typical magnitude decrement due to differential rotation with $V_e = 300$ km/s is 1 mag, but it could be even larger according to Bodenheimer.

Uniform rotation with $V_e \approx 200$ km/s would not greatly change the effective temperature of a massive main-sequence star, thus probably accounting for the agreement between theoretical nonrotating stellar models and the 15 "normal" stars in our sample. Nonuniform rotation, however, seems the only way to explain the observed properties of the primaries of μ^1 Sco and V356 Sgr, and is in accord with evolutionary theories concerning these two systems. A possible check on our idea would be to show from an analysis of accurate light curves that the shapes of the primaries are inconsistent with their observed surface rotation and the hypothesis of uniform rotation. In the case of μ^1 Sco, the orbital inclination may be too small (60°), and the tidal distortion too great[23], to make a reliable check. In the case of V356 Sgr, the orbital inclination is approximately 90° and the components are well separated. The difficulties encountered by Popper[20] in analysing the light curve of this system might lead one to suspect that the primary does indeed have an anomalous shape. It would be worthwhile for someone to reobserve and reanalyse these two systems in more detail, along the lines recently begun, for example, by Wilson and Devinney[24].

Returning to the problem of β Lyr, we suggest that, if the "secondary" has already accreted most of its massive disk, it may be in rapid, highly nonuniform rotation. It could easily be underluminous by 2 mag, or more, for its mass. (Devinney's observational estimate of the amount of underluminosity, 4 mag, is probably an upper limit, as may be judged from his published data[12]; a value of 2 mag seems more reasonable and has, in fact, been estimated by Woolf[15].) The secondary would further be expected to exhibit all the emission characteristics of an extreme Be star, but these will, of course, be considerably modified by the presence of the remnant disk. Woolf[25] has pointed out that the secondary should be the less evolved component, on the basis of elementary considerations of evolution as outlined above, and he has also[15] mentioned several analogies between this system and the somewhat more evolved system V356 Sgr. In contrast, Devinney's alternative theory of the origin of the disk[12], which is similar to that proposed[8] for the disk in ε Aur, does not account for the peculiar properties of the primary, such as the filling of its Roche lobe and its hydrogen deficiency (compare the apparently normal primary in ε Aur whose separation from the secondary is probably too great for the components ever to have interacted significantly). These reasons make it hard to believe that a collapsar is embedded in the disk of β Lyr (unless a second phase of mass transfer has again interchanged the roles of primary and secondary—but time scale arguments militate against the probability of observing such systems). Accretion of matter from the remnant disk would still occur for the massive secondary, and may, then, still account for the "blue" spectral energy distribution that is observed[13,26].

We conclude that, before the inference of a collapsar in β Lyr and in similar systems (such as υ Sgr, KS Per, UW CMa, V353 Sco, and HD 47129) can be made plausible, the more likely explanation of differential rotation must be investigated more fully. In particular, it would be valuable to determine theoretically the maximum amount of underluminosity for a model of the secondary of β Lyr that is compatible with dynamical stability and with the requirement that the equatorial radius does not exceed the size of the Roche lobe.

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Did Southern Africa and North America Drift Independently during the Precambrian?

THE pattern of continental drift and seafloor spreading since the Jurassic is well established, and there is now some interest in investigating pre-Mesozoic drift[1,2] using palaeomagnetism. Comparison of pole paths from different continental plates over the same intervals of geological time to see whether they can be superimposed indicates whether during these intervals the two plates were contiguous[3]. Because the Precambrian occupies over 80% of geological time, palaeomagnetism is important in deciding whether continental drift has been a catastrophic or a uniformitarian event in Earth history. This communication describes an attempt to reconcile the presently defined Precambrian pole paths for Southern Africa and North America in terms of the computer fit of the continents around the Atlantic[16].

Palaeomagnetic studies of Precambrian rock units involve four important factors. First, the isotopic age may be resolvable only to 100 million years (m.y.)[4]. Second, the Precambrian record is nowhere complete: thus it may prove impossible either to show consistency in the pole path using rocks of the same age but from different locations, or even to construct a representative pole path for certain continents. Third, the present continents may not always have been single Precambrian cratons: they may have formed by welding of several plates[5]. Fourth, the magnetic stability and reliability of Precambrian rocks must be carefully established[6].

McElhinny *et al.*[7] constructed Precambrian pole paths for the Rhodesian and Transvaal shields of Southern Africa (Fig. 1). Some twenty determinations were used from separate rock units ranging in apparent age from 1,310 to 2,630 m.y. Although the poles were of high magnetic quality, the isotopic ages of some of these rock units were considered to be preliminary. In Fig. 1, note the apparent inconsistency between the isotopic and magnetic ages for P7, the 1,430–1,640 m.y. Mashonaland dolerites[20], and P8, the 1,750 m.y. Premier Mine Kimberlite[21]. Nevertheless the agreement between poles from diverse igneous rocks and the thick red bed sequence of the Waterberg Series[22] provided a good consistency test for the pole path during the interval 1,310–1,950 m.y. Additional data for younger rocks from Tanzania do not simply fit into this pole path[8] and may indicate that the Tanzania and Rhodesian/Transvaal cratons behaved as separate plates during the Precambrian. For the interval 2,100–2,630 m.y., two alternate paths were proposed[7], because of the large distances of arc required to join poles from 1,950 and 2,100 m.y. rock units respectively.

Although palaeomagnetic studies have been made on rocks from Australia[9] and the Baltic shield[10], North America is the only other continent where sufficient numbers of dated Precambrian poles of different age allow a representative pole path